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(54) **MICROELECTROMECHANICAL
GYROSCOPE WITH ROTARY DRIVING
MOTION AND IMPROVED ELECTRICAL
PROPERTIES**

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(56) **References Cited**

U.S. PATENT DOCUMENTS

4,159,125 A 6/1979 Buchwald

4,744,248 A 5/1988 Stewart

(Continued)

FOREIGN PATENT DOCUMENTS

DE 102006046772 A1 4/2008

EP 1619471 A1 1/2006

(Continued)

OTHER PUBLICATIONS

Schofield, A.R. et al., "Multi-Degree of Freedom Tuning Fork
Gyroscope Demonstrating Shock Rejection," IEEE Sensors 2007
Conference, Atlanta, Georgia, Oct. 28-31, 2007, pp. 120-123.

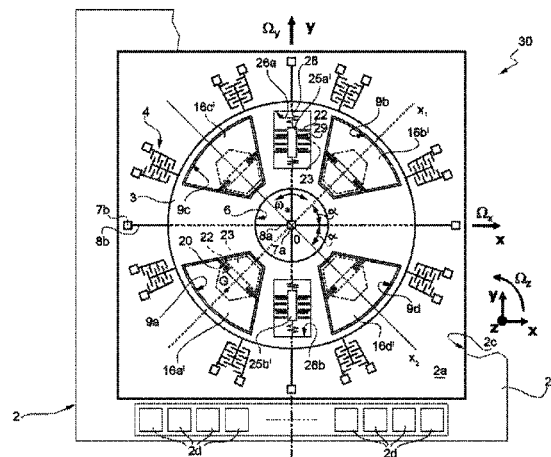
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(57) **ABSTRACT**

An integrated microelectromechanical structure is provided
with: a die, having a substrate and a frame, defining inside
it a detection region and having a first side extending along
a first axis; a driving mass, anchored to the substrate, set in
the detection region, and designed to be rotated in a plane
with a movement of actuation about a vertical axis; and a
first pair and a second pair of first sensing masses, suspended
inside the driving mass via elastic supporting elements so as
to be fixed with respect thereto in the movement of actuation
and so as to perform a detection movement of rotation out
of the plane in response to a first angular velocity; wherein
the first sensing masses of the first pair and the first sensing
masses of the second pair are aligned in respective direc-
tions, having non-zero inclinations of opposite sign with
respect to the first axis.

21 Claims, 7 Drawing Sheets



(56)

References Cited

U.S. PATENT DOCUMENTS

4,750,364 A 6/1988 Kawamura et al.
 5,392,650 A 2/1995 O'Brien et al.
 5,447,068 A 9/1995 Tang
 5,728,936 A 3/1998 Lutz
 5,895,850 A 4/1999 Buestgens
 6,230,563 B1 5/2001 Clark et al.
 6,250,156 B1 6/2001 Seshia et al.
 6,308,567 B1 10/2001 Higuchi et al.
 6,349,597 B1 2/2002 Folkmer et al.
 6,513,380 B2 2/2003 Reeds, III et al.
 6,520,017 B1 2/2003 Schoefthaler et al.
 6,535,800 B2 3/2003 Wallner
 6,722,197 B2 4/2004 Knowles et al.
 6,725,719 B2 4/2004 Cardarelli
 6,752,017 B2 6/2004 Willig et al.
 6,766,689 B2 7/2004 Spinola Durante et al.
 6,837,107 B2 1/2005 Geen
 6,845,665 B2 1/2005 Geen
 6,848,304 B2 2/2005 Geen
 6,928,872 B2 8/2005 Durante et al.
 7,155,976 B2 1/2007 Kai-Cheng et al.
 7,240,552 B2 7/2007 Acar et al.
 7,284,429 B2 10/2007 Chaumet et al.
 7,322,242 B2 1/2008 Merassi et al.
 7,347,094 B2 3/2008 Geen et al.
 7,398,683 B2 7/2008 Lehtonen
 7,454,246 B2 11/2008 Merfeld
 7,461,552 B2 12/2008 Acar
 7,481,111 B2 1/2009 Caminada et al.
 7,513,155 B2 4/2009 Jeong et al.
 7,694,563 B2 4/2010 Durante et al.
 7,765,869 B2 8/2010 Sung et al.
 7,797,998 B2 9/2010 Menard et al.
 7,907,177 B2 3/2011 Haino et al.
 7,950,281 B2 5/2011 Hammerschmidt
 8,020,441 B2 9/2011 Seeger
 8,037,756 B2 10/2011 Caminada et al.
 8,037,757 B2 10/2011 Johnson
 8,042,394 B2 10/2011 Coronato et al.
 8,042,396 B2 10/2011 Coronato et al.
 8,117,912 B2 2/2012 Kawakubo et al.
 8,250,921 B2 8/2012 Nasiri et al.

8,256,290 B2 9/2012 Mao
 8,261,614 B2 9/2012 Hartmann et al.
 8,272,267 B2 9/2012 Tamura et al.
 8,312,769 B2 11/2012 Coronato et al.
 8,342,023 B2 1/2013 Geiger
 8,342,025 B2 1/2013 Coronato et al.
 8,347,716 B2 1/2013 Cazzaniga et al.
 8,347,717 B2 1/2013 Seeger et al.
 8,353,212 B2 1/2013 Hammer
 8,375,789 B2 2/2013 Prandi et al.
 8,429,970 B2 4/2013 Rocchi
 8,459,109 B2 6/2013 Caminada et al.
 8,459,110 B2 6/2013 Cazzaniga et al.
 8,464,585 B2 6/2013 Raman et al.
 8,534,127 B2 9/2013 Seeger et al.
 8,549,919 B2 10/2013 Günthner et al.
 8,616,057 B1 12/2013 Mao
 8,667,842 B2 3/2014 Prandi
 8,960,002 B2 2/2015 Nasiri et al.
 9,003,882 B1 4/2015 Ayazi et al.
 9,010,184 B2 4/2015 Zou et al.
 9,038,461 B2 5/2015 Kanemoto
 9,194,704 B2 11/2015 Lin et al.
 2002/0078746 A1 6/2002 Mochida
 2002/0189351 A1 12/2002 Reeds et al.
 2003/0131664 A1 7/2003 Mochida et al.
 2006/0112764 A1 6/2006 Higuchi
 2007/0062282 A1 3/2007 Akashi et al.
 2008/0276706 A1 11/2008 Hartmann et al.
 2010/0149721 A1 6/2010 Prandi
 2010/0192690 A1 8/2010 Classen et al.
 2011/0030473 A1 2/2011 Acar
 2012/0024056 A1 2/2012 Hammer
 2012/0031977 A1 2/2012 Havens et al.
 2012/0048017 A1 3/2012 Kempe
 2012/0060604 A1 3/2012 Neul et al.
 2013/0167636 A1 7/2013 Coronato et al.

FOREIGN PATENT DOCUMENTS

EP 2108964 A2 10/2009
 JP 2005-241500 A 9/2005
 WO 2006/043890 A1 4/2006
 WO 2007/086849 A1 8/2007
 WO 2007/145113 A1 12/2007
 WO 2009/033915 A1 3/2009

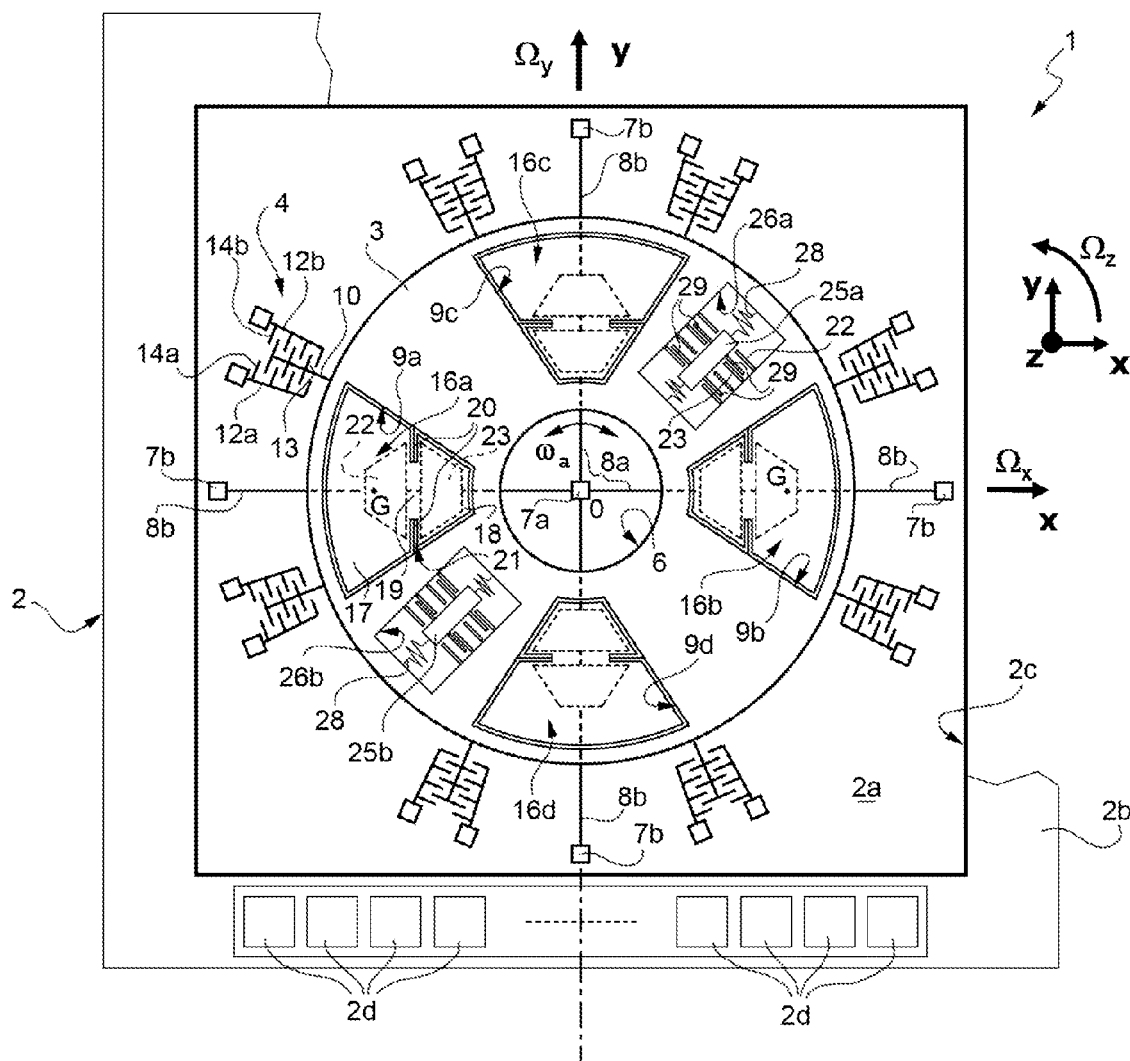


FIG. 1
(Prior Art)

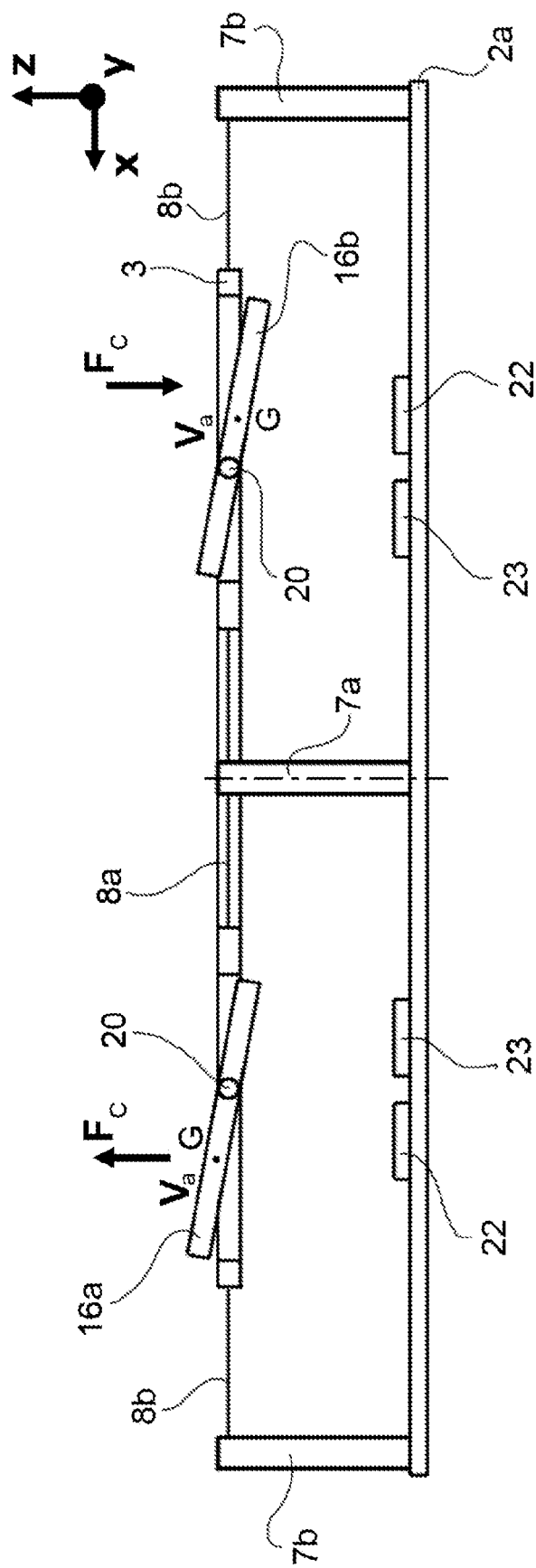


FIG. 2
(Prior Art)

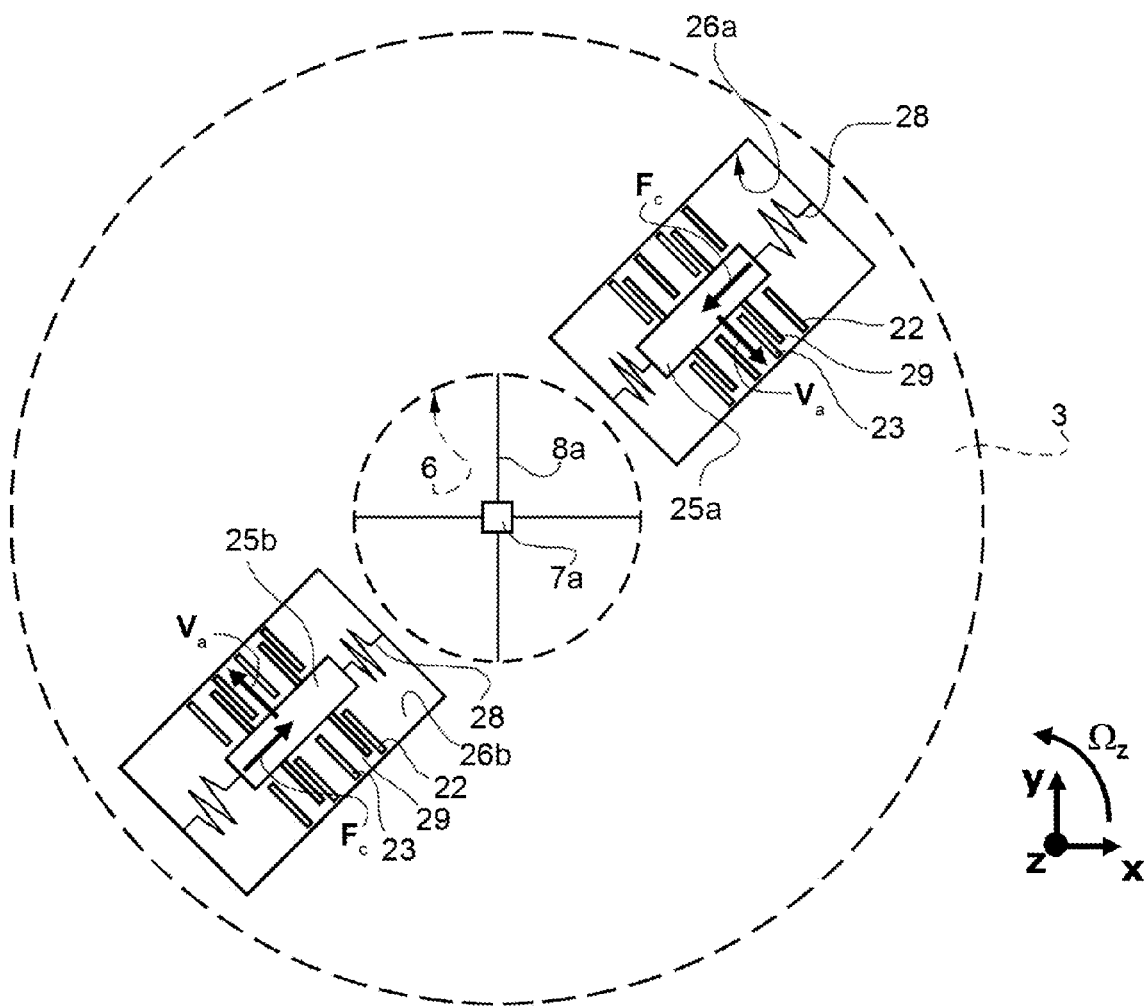


FIG. 3
(Prior Art)

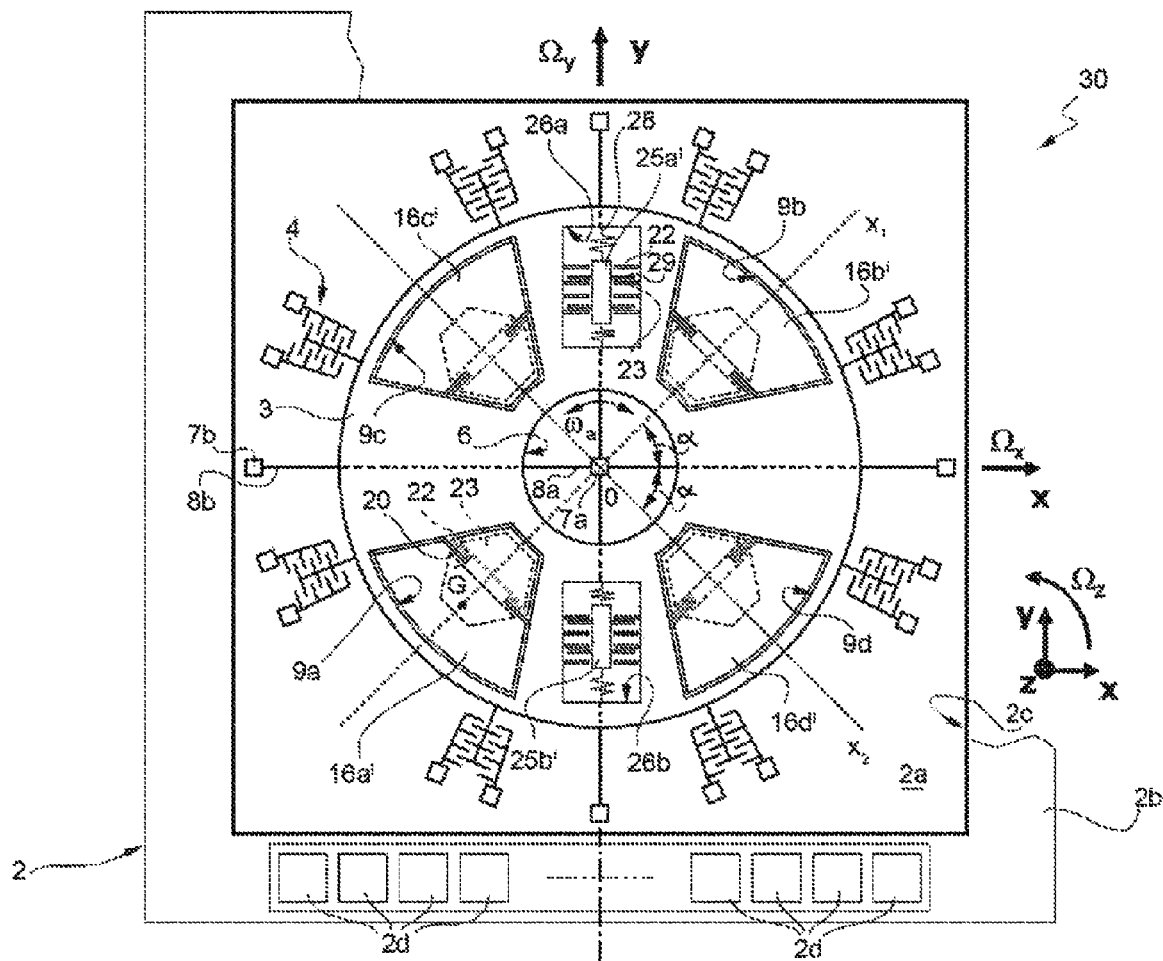


FIG. 4

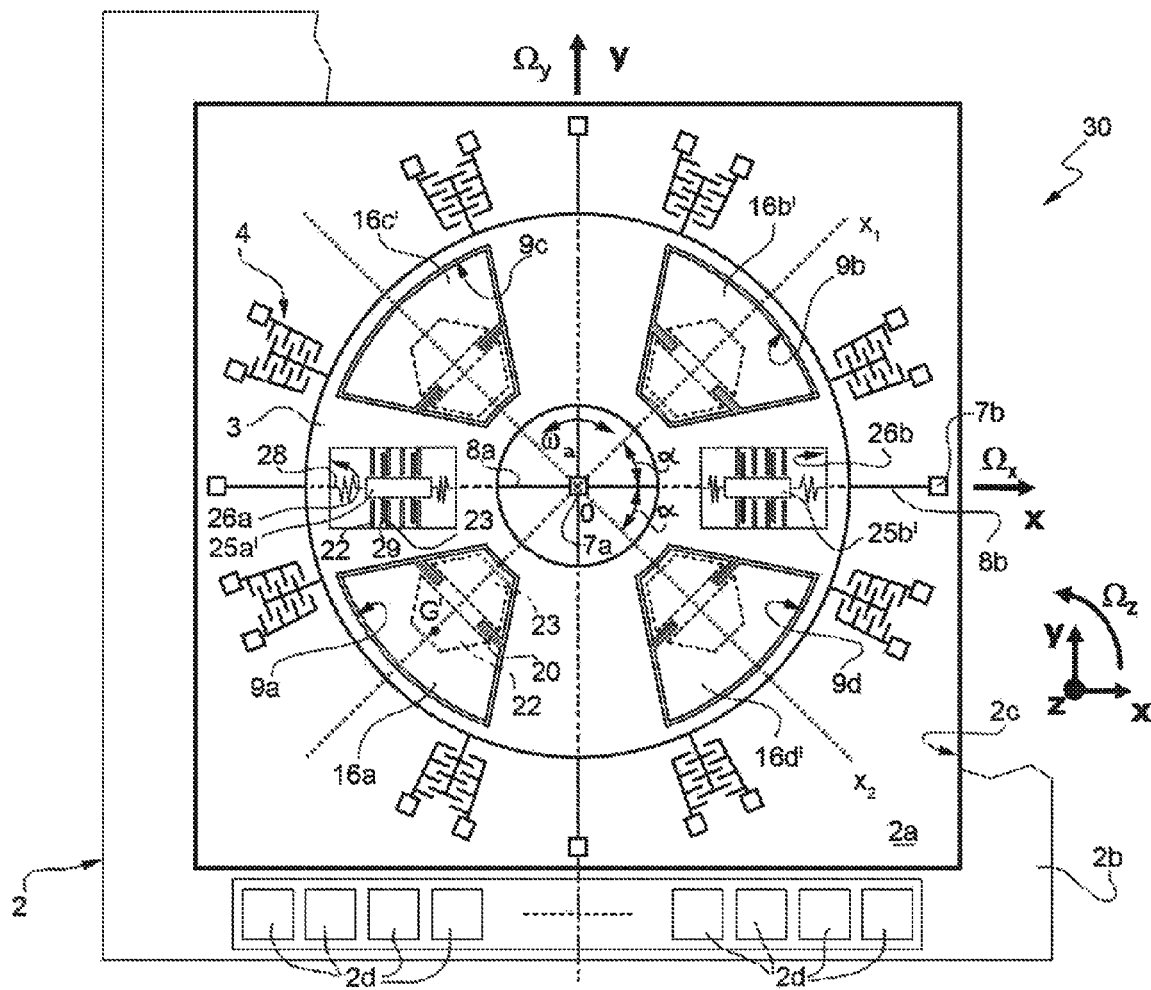


FIG. 5

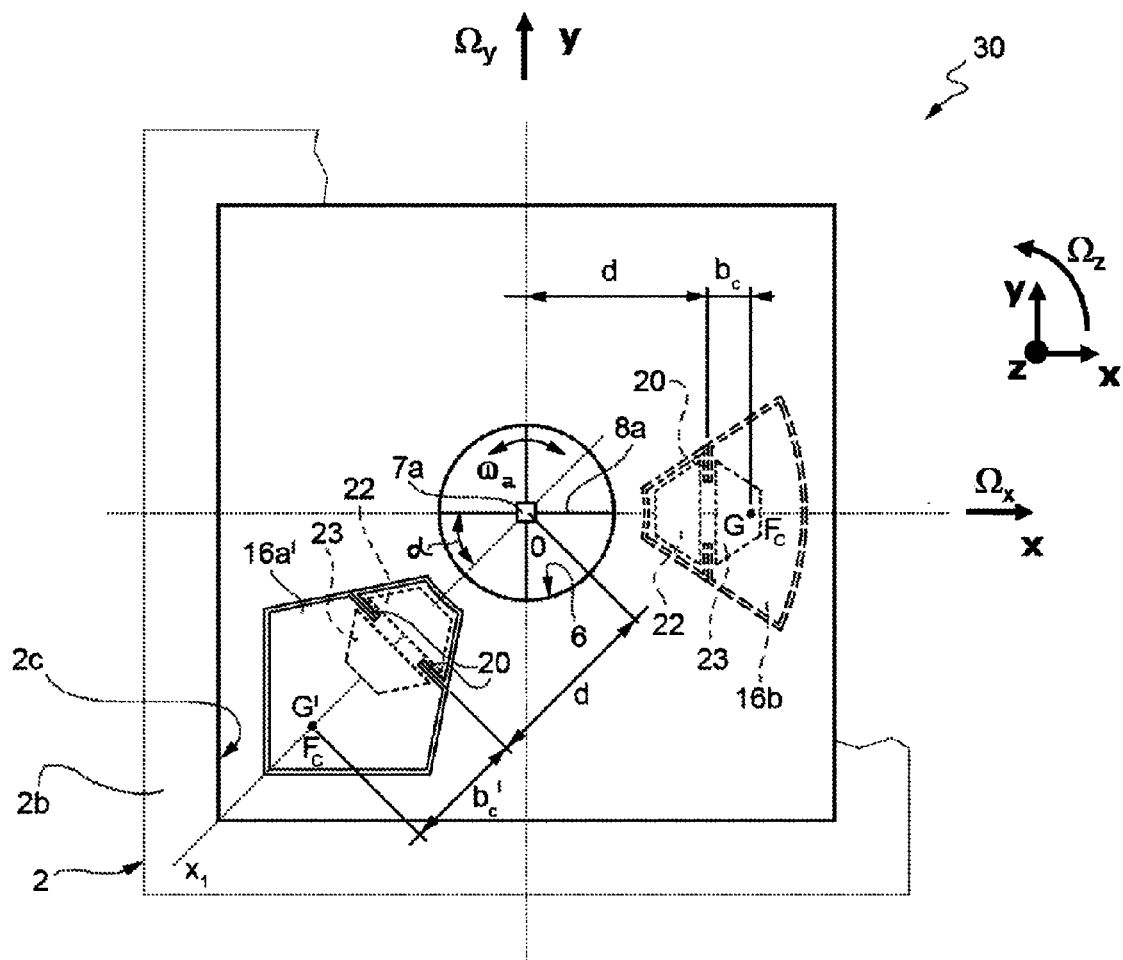


FIG. 6

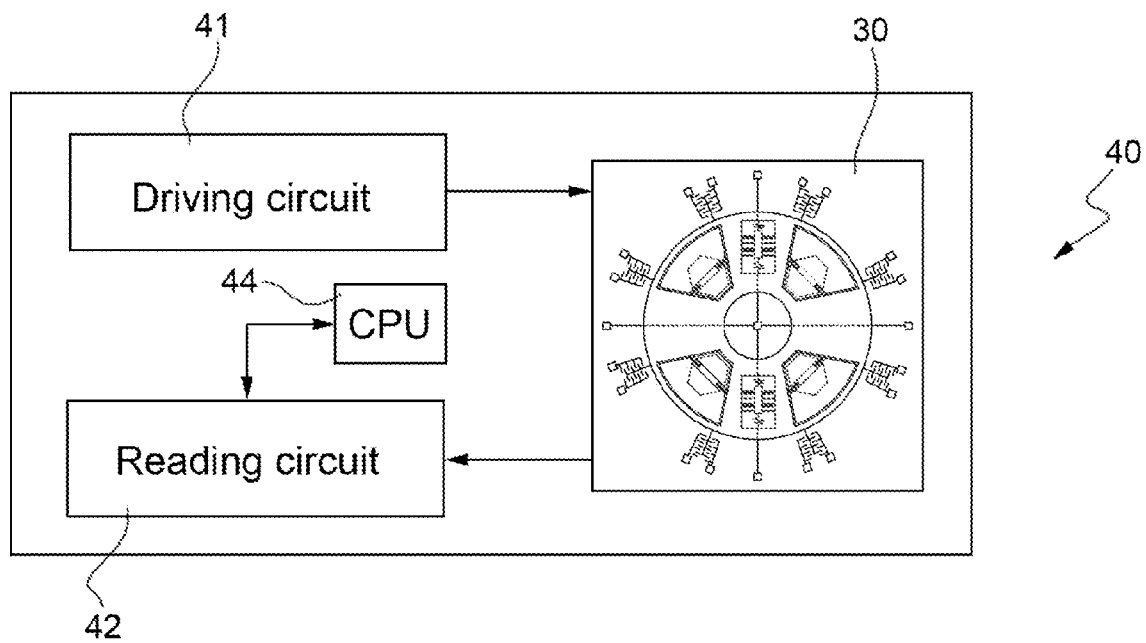


FIG. 7

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MICROELECTROMECHANICAL GYROSCOPE WITH ROTARY DRIVING MOTION AND IMPROVED ELECTRICAL PROPERTIES

BACKGROUND

1. Technical Field

The present disclosure relates to a microelectromechanical structure, in particular a biaxial or triaxial gyroscope, provided with a rotary driving movement and improved electrical characteristics, in particular in terms of sensitivity in the detection of angular velocities.

2. Description of the Related Art

As is known, micromachining techniques enable manufacturing of microelectromechanical structures or systems (MEMS) within layers of semiconductor material, which have been deposited (for example, a polycrystalline-silicon layer) or grown (for example, an epitaxial layer) on sacrificial layers, which are removed via chemical etching.

Inertial sensors, accelerometers, and gyroscopes obtained with this technology are having an increasing success, for example, in the automotive field, in inertial navigation, or in the field of portable devices.

In particular, known to the art are integrated gyroscopes made of semiconductor material obtained with MEMS technology. These gyroscopes operate on the basis of the theorem of relative accelerations, exploiting the Coriolis acceleration. When an angular velocity is applied to a mobile mass that moves at a linear velocity, the mobile mass “feels” an apparent force, referred to as “Coriolis force”, which causes a displacement thereof in a direction perpendicular to the direction of the linear velocity and to the axis about which the angular velocity is applied. The mobile mass is supported via springs that enable a displacement thereof in the direction of the apparent force. On the basis of Hooke’s law, the displacement is proportional to the apparent force, in such a way that from the displacement of the mobile mass it is possible to detect the Coriolis force and the value of the angular velocity that has generated it. The displacement of the mobile mass can, for example, be detected in a capacitive way by determining, in resonance conditions, the variations of capacitance caused by the movement of mobile electrodes, fixed with respect to the mobile mass and combfingered with fixed electrodes.

The published US patent applications US 2007/0214883, US 2009/0064780, and US 2009/0100930, filed by the applicant of the present application, disclose an integrated microelectromechanical sensor with rotary driving movement and sensitive to angular velocities of pitch, roll, and yaw about respective axes of detection.

This microelectromechanical sensor comprises a single driving mass, anchored to a substrate in a single central point, and actuated with rotary motion about an axis passing through the central point and orthogonal to the plane of the driving mass. The movement of rotation of the driving mass makes it possible to obtain in the plane of the mass two components of driving velocity orthogonal with respect to one another. Through openings are provided within the driving mass, and corresponding sensing masses are arranged in the through openings; the sensing masses are enclosed in the overall dimensions of the driving mass, are suspended with respect to the substrate, and are connected to the driving mass via flexible elements. Each sensing mass is fixed with respect to the driving mass during its rotary motion, and has a further degree of freedom of movement as a function of an external stress, in particular a Coriolis force,

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acting on the sensor. The flexible elements, thanks to their particular construction, enable the sensing masses to perform a rotary movement of detection about an axis belonging to the plane of the sensor, or alternatively a linear movement of detection along an axis belonging to the plane of the sensor, respectively, in response to a Coriolis acceleration acting in a direction perpendicular to the plane and to a Coriolis acceleration acting in a direction belonging to the plane. The movement of detection is in any case substantially decoupled from the movement of actuation of the driving mass. This microelectromechanical structure, in addition to being compact (in so far as it envisages a single driving mass enclosing in its overall dimensions a number of sensing masses), makes it possible to obtain with minor structural modifications, a uniaxial, biaxial, or triaxial gyroscope (and/or possibly an accelerometer, according to the electrical connections implemented), at the same time ensuring an excellent decoupling of the driving dynamics from the detection dynamics.

FIG. 1 shows an exemplary embodiment of a triaxial microelectromechanical gyroscope, designated by 1, according to the teachings contained in the aforesaid patent applications.

The gyroscope 1 is made in a die 2, comprising a substrate 2a made of semiconductor material (for example, silicon), and a frame 2b defining inside it an open region 2c; the open region 2c overlies the substrate 2a, and is designed to house detection structures of the gyroscope 1 (as described in detail hereinafter). The open region 2c has a generally square or rectangular configuration in a horizontal plane (in what follows, plane of the sensor xy), defined by a first horizontal axis x and a second horizontal axis y, fixed with respect to the die 2. The frame 2b has sides that are substantially parallel to the horizontal axes x, y. Contact pads 2d (so-called “die pads”) are arranged along a side of the frame 2b, aligned, for example, along the first horizontal axis x. In a way not illustrated, the die pads 2d enable electrical contact from outside of the detection structures of the gyroscope 1. The die pads 2d have an axis of symmetry, in this case coinciding with the second horizontal axis y (orthogonal to their direction of alignment), and are arranged in equal number and in a specular way on opposite sides of the second horizontal axis y.

In particular, the first and second horizontal axes x, y correspond to a first axis of detection and to a second axis of detection of the gyroscope 1 (more precisely, to a pitch axis and to a roll axis), about which corresponding pitch and roll angular velocities $\vec{\Omega}_x$ and $\vec{\Omega}_y$ are detected.

In detail, the gyroscope 1 comprises a driving structure, housed within the open region 2c and including a driving mass 3 and a driving assembly 4.

The driving mass 3 has a generally circular geometry with radial symmetry, with a substantially planar configuration having a main extension in the plane of the sensor xy, and a negligible dimension, with respect to the main extension, in a direction parallel to a vertical axis z, forming with the first and second horizontal axes x, y a set of three orthogonal axes, fixed with respect to the die 2. For example, the driving mass 3 has in the plane of the sensor xy basically the shape of an annulus, and defines at the center an empty space 6, the center O of which coincides with the center of gravity and the center of symmetry of the entire structure.

The driving mass 3 is anchored to the substrate 2a by means of a first anchorage 7a set in an area corresponding to the center O, to which it is connected through first elastic anchorage elements 8a. In the example, the first elastic

anchorage elements **8a** depart, forming a cross, from the center O, parallel to the first and second horizontal axes x, y. The driving mass **3** is anchored to the substrate **2a** by means of further anchorages **7b**, set on the outside of the same driving mass **3**, to which it is connected by means of further elastic anchorage elements **8b**. For example, the further elastic anchorage elements **8b** are of the folded type, are four in number, and are set aligned in pairs along the first and second horizontal axes x, y; accordingly, the further anchorages **7b** are arranged, in pairs, on opposite sides of the driving mass **3** with respect to the empty space **6**, at the ends of a cross centered in the center O. The first and further elastic anchorage elements **8a**, **8b** enable a rotary movement of the driving mass **3** about an axis of actuation passing through the center O, parallel to the vertical axis z and perpendicular to the plane of the sensor xy.

The driving mass **3** has: a first pair of first through openings **9a**, **9b**, aligned in a diametric direction along the first horizontal axis x (pitch axis), and set on opposite sides with respect to the empty space **6**; and a second pair of first through openings **9c**, **9d**, aligned in a diametric direction along the second horizontal axis y (roll axis), and set on opposite sides with respect to the empty space **6**. In particular, each of the first through openings **9a-9d** has in the plane of the sensor xy the shape of a radial sector of an annulus, having arc-shaped internal and external sides and radially-extending lateral sides. In addition, the through openings **9a**, **9b** of the first pair are symmetrical with respect to the second horizontal axis y, and the through openings **9c**, **9d** of the second pair are symmetrical with respect to the first horizontal axis x. Moreover, the driving mass **3** has a pair of second through openings **26a**, **26b**, having in plan view a substantially rectangular shape, aligned in a radial direction (in the example of FIG. 1 in a direction inclined by 45° with respect to the first horizontal axis x or the second horizontal axis y), and having a main extension in the same radial direction.

The driving assembly **4** comprises a plurality of driven arms **10**, extending externally from the driving mass **3** in a radial direction and in such a way that they are set at equal angular distances apart, and a plurality of first and second driving arms **12a**, **12b**, which extend parallel to, and on opposite sides of, respective driven arms **10**. Each driven arm **10** carries a plurality of first electrodes **13**, extending perpendicular to, and on either side of, the same driven arm. In addition, each of the first and second driving arms **12a**, **12b** carries respective second electrodes **14a**, **14b**, which extend towards the respective driven arm **10** and are comb-fingered with the corresponding first electrodes **13**. The first driving arms **12a** are arranged all on one and the same side of the respective driven arms **10**, and are biased all at one and the same first voltage. Likewise, the second driving arms **12b** are arranged all on the opposite side of the respective driven arms **10**, and are biased all at one and the same second voltage. A driving circuit (not illustrated) is connected to the second electrodes **14a**, **14b** for applying the first and second voltages and determining, by means of the mutual and alternating attraction of the electrodes, an oscillatory rotary movement of the driving mass **3** about the axis of actuation, at a given frequency of oscillation.

The gyroscope **1** further comprises a first pair of acceleration sensors with axis parallel to the vertical axis z, and in particular a first pair of first sensing masses **16a**, **16b**, set within a respective first through opening **9a**, **9b** so as to be completely enclosed and contained within the overall dimensions of the driving mass **3** in the plane of the sensor xy. Each of the first sensing masses **16a**, **16b** has a shape

corresponding to that of the respective through opening, and consequently has, in a plan view, the general shape of a radial annulus sector. In detail, each of the first sensing masses **16a**, **16b** has a first portion **17**, which is wider, and a second portion **18**, which is narrower (along the first horizontal axis x), these portions being connected by a connecting portion **19**, which is shorter (in a direction parallel to the second horizontal axis y) than the first and second portions **17**, **18**, and consequently has a center of gravity G located within the corresponding first portion **17**. In greater detail, the first portion **17** has an outer side that is arc-shaped and concave, and radially-extending lateral sides, and the second portion **18** has an outer side that is arc-shaped and convex and radially-extending lateral sides, aligned along the lateral sides of the first portion **17**. Each of the first sensing masses **16a**, **16b** is supported by a pair of first elastic supporting elements **20**, extending from the connecting portion **19** to the driving mass **3**, connecting thereto, parallel to the second horizontal axis y. The first elastic supporting elements **20** extend within recesses **21** provided on opposite sides of the corresponding first sensing mass **16a**, **16b**, at a distance from its center of gravity G. The first elastic supporting elements **20** form torsional springs which are rigid in regard to the rotary motion of the driving mass **3** (so that the first sensing masses **16a**, **16b** follow the driving mass **3** in its motion of actuation), and moreover enable rotation of the first sensing masses about an axis of rotation parallel to the second horizontal axis y and belonging to the plane of the sensor xy, and hence their movement out of the plane of the sensor xy (a movement that is not, instead, allowed for the driving mass **3**).

The gyroscope **1** further comprises a second pair of acceleration sensors with axis parallel to the vertical axis z, and in particular a second pair of first sensing masses **16c**, **16d**, housed within the through openings **9c**, **9d**, and completely enclosed and contained by the driving mass **3**. The first sensing masses **16c**, **16d** are obtained from the rotation through 90° of the first sensing masses **16a**, **16b** with respect to the center O, and consequently the corresponding elastic supporting elements **20** extend parallel to the first horizontal axis x and enable rotation out of the plane of the sensor xy, about an axis of rotation parallel to the first horizontal axis x.

A pair of first and second sensing electrodes **22**, **23** is set underneath the first and second portions **17**, **18** of each of the first sensing masses **16a-16d**. The first and second sensing electrodes **22**, **23** are made of polycrystalline-silicon regions formed on the substrate **2a** and having a substantially trapezoidal shape and dimensions substantially corresponding to those of the second portion **18**. The first and second sensing electrodes **22**, **23** are separated, respectively, from the first and second portions **17**, **18**, by an air gap, and hence form, together with the first and second portions **17**, **18**, respective sensing capacitors. The first and second sensing electrodes **22**, **23** are connected to a read circuit of the gyroscope **1** (not illustrated) via the connection pads **2d**.

The gyroscope **1** further comprises a pair of second sensing masses **25a**, **25b** housed within the second through openings **26a**, **26b**. The second sensing masses **25a**, **25b** have a generally rectangular shape with sides parallel to corresponding sides of the second through openings **26a**, **26b**, are suspended with respect to the substrate **2a**, and are connected to the driving mass **3** via second elastic supporting elements **28**. The second elastic supporting elements **28** depart, for example, from a point set approximately at the center of the minor sides of the second sensing masses, in the radial direction. In particular, the second elastic supporting

elements **28** are rigid with respect to the motion of actuation of the driving mass **3** (in such a way that the second sensing masses **25a**, **25b** follow the driving mass **3** in its rotary movement), and moreover enable a linear movement of the respective second sensing masses in the aforesaid radial direction. In addition, the second sensing masses **25a**, **25b** have prolongations **29** extending, for example, starting from a point set approximately at the center of corresponding major sides, in a direction orthogonal to the radial direction. These prolongations **29** form sensing capacitors with plane and parallel faces with fixed electrodes anchored to the substrate, set facing, and parallel to, the same prolongations **29**. For example, from each major side of each second sensing mass **25a**, **25b** departs a respective prolongation **29**, which faces, and is set between, two fixed electrodes. In a way similar to what has been described previously, the fixed electrodes set in a radially more external position with respect to the center O are defined as "first sensing electrodes **22**", and the fixed electrodes set in a radially more internal position are defined as "second sensing electrodes **23**".

In use, the gyroscope **1** is able to operate as a triaxial gyroscope, and to detect a pitch angular velocity $\vec{\Omega}_x$ about the first horizontal axis x, a roll angular velocity $\vec{\Omega}_y$ about the second horizontal axis y, and a yaw angular velocity $\vec{\Omega}_z$ about the vertical axis z.

With reference also to FIG. 2, the rotary movement of the driving mass **3** and of the first sensing masses **16a-16d** about the axis of actuation can be represented by a driving-velocity vector \vec{v}_a , tangential to the circumference describing the path thereof. In particular, the rotary motion about the first horizontal axis x or the second horizontal axis y with angular velocity $\vec{\Omega}_x$, $\vec{\Omega}_y$ causes a Coriolis force (designated by \vec{F}_C) acting on the entire structure, proportional to the vector product between the angular velocity $\vec{\Omega}_x$, $\vec{\Omega}_y$; and the driving velocity \vec{v}_a , and hence directed along the vertical axis z. On the entire structure, considered as a single rigid body, it is hence possible to identify a distribution of Coriolis forces, the value of which increases as the distance from the center O increases. The resultants of the Coriolis force \vec{F}_C acting on the first sensing masses **16a-16d** at the corresponding center of gravity G, cause rotation of the first sensing masses, which move out of the plane of the sensor xy, about an axis parallel to the first horizontal axis x or the second horizontal axis y and passing through the first elastic supporting elements **20**. This movement is allowed by the torsion of the first elastic supporting elements **20**. Instead, the configuration of the first and further elastic anchorage elements **8a**, **8b** is such as to inhibit, to a good approximation, the movement of the driving mass **3** out of the plane of the sensor xy, in this way enabling the effective decoupling of the motion of detection of the sensing masses with respect to that of actuation. The displacement of the first sensing masses **16a-16d** out of the plane of the sensor xy causes a differential capacitive variation of the sensing capacitors, the value of which is proportional to the angular velocity $\vec{\Omega}_x$, $\vec{\Omega}_y$, which can thus be determined, via an appropriate read circuit, operating according to a differential scheme.

In particular, since the reading scheme is differential, the configuration in pairs of the first sensing masses **16a-16d** enables automatic rejection of linear spurious accelerations along the vertical axis z. In addition, a rotation about the first

horizontal axis x is not felt by the second pair of first sensing masses **16c**, **16d**, in so far as the resultant Coriolis force \vec{F}_C is zero (since the vector product between the angular velocity $\vec{\Omega}_x$ and the corresponding driving velocity \vec{v}_a goes to zero). Likewise, the rotation about the second horizontal axis y is not felt for similar reasons by the first pair of first sensing masses **16a**, **16b** so that the two axes of detection are not affected and are substantially decoupled.

With reference to FIG. 3, an angular velocity $\vec{\Omega}_z$ to be detected, acting about the vertical axis z, generates a Coriolis force \vec{F}_C on the second sensing masses **25a**, **25b** set in a radial direction (hence directed as a centrifugal force acting on the same masses), causing displacement of the second sensing masses and a capacitive variation of the corresponding sensing capacitors. The value of the capacitive variation is proportional to the angular velocity $\vec{\Omega}_z$, which can be determined, via the read circuit, operating again according to a differential scheme.

Advantageously, the particular conformation of the first sensing masses **16a-16d** enables an increase in the sensitivity of the gyroscope **1** (as compared to the use of other geometries for the same first sensing masses). In particular, the corresponding center of gravity G is positioned at a distance from the first elastic supporting elements **20** (and the corresponding axis of rotation out of the plane of the sensor xy) that is greater than that of the center of gravity of any rectangular mass that can be inscribed in one and the same sector of the driving mass **3** and is supported by elastic supporting elements extending along the same axis of rotation. Consequently, it is possible to obtain a higher twisting moment, and hence a greater movement of rotation out of the plane of the sensor xy, and in this way obtains a higher sensitivity of the sensor.

In addition, the presence of the further elastic anchorage elements **8b**, located outside the driving mass **3**, enables increase of the stiffness of the driving mass **3** in regard to the movements out of the plane of the sensor xy, and so an increase in the decoupling between the driving movement and the movements of detection.

Even though the described gyroscope represents a considerable improvement over other gyroscopes of a known type, it is not altogether optimized in respect of manufacturing simplicity, size reduction, efficiency in terms of electrical characteristics, and immunity to disturbance.

BRIEF SUMMARY

One embodiment is a microelectromechanical (MEMS) gyroscope that is improved in regards to sensitivity to external stresses and robustness in regard to disturbance. The MEMS gyroscope includes a die, having a substrate and a frame, where the frame has a detection region and a first side extending along a first horizontal axis. The MEMS gyroscope also includes a driving mass, anchored to the substrate via elastic anchorage elements, set in the detection region, and designed to be rotated in a plane with a movement of actuation about a vertical axis, and a first pair and a second pair of first sensing masses, suspended inside, and coupled to, the driving mass via respective elastic supporting elements so as to be fixed with respect thereto in the movement of actuation and perform a detection movement of rotation out of the plane in response to a first angular velocity. The first sensing masses of the first pair and the first sensing masses of the second pair being aligned in respec-

tive directions, having non-zero inclinations of opposite sign with respect to the first horizontal axis.

BRIEF DESCRIPTION OF THE SEVERAL VIEWS OF THE DRAWINGS

For a better understanding of the present disclosure, preferred embodiments thereof are now described purely by way of non-limiting example and with reference to the attached drawings, wherein:

FIG. 1 shows a schematic top plan view of a microelectromechanical gyroscope, of a known type;

FIGS. 2 and 3 show, respectively, a schematic lateral cross-sectional view and a schematic top plan view, of parts of the gyroscope of FIG. 1, in the presence of a Coriolis force;

FIG. 4 shows a schematic top plan view of a microelectromechanical gyroscope according to a first embodiment of the present disclosure;

FIG. 5 shows a schematic top plan view of a second embodiment of the microelectromechanical gyroscope;

FIG. 6 shows the schematic comparison between a portion of the microelectromechanical gyroscope, in a further variant embodiment thereof, and a corresponding portion of a sensor; and

FIG. 7 shows a simplified block diagram of an electronic device provided with the microelectromechanical gyroscope according to the present disclosure.

DETAILED DESCRIPTION

As will be described in detail hereinafter, an aspect of the present disclosure envisages providing a microelectromechanical gyroscope having an arrangement of the sensing masses such as to enable an increase in the sensitivity of the sensor and in general an improvement of its electrical characteristics.

As is shown in FIG. 4, where the same reference numbers are used for indicating elements similar to others already described with reference to FIG. 1, the microelectromechanical gyroscope, here designated by 30, differs from the gyroscope 1 of FIG. 1 substantially on account of a different arrangement of the first sensing masses, here designated by 16a'-16d', and of the second sensing masses, here designated by 25a', 25b'.

In greater detail, the first sensing masses 16a', 16b' of the first pair are aligned in a first diametric direction x_1 , inclined with respect to the first horizontal axis x of the die 2 by an angle of inclination α (considered in a counterclockwise direction), the value of which is preferably 45°. Likewise, the first sensing masses 16c', 16d' of the second pair are aligned in a second diametric direction x_2 , substantially orthogonal to the first diametric direction x_1 , and inclined with respect to the first horizontal axis x by the same angle of inclination α (considered in this case in an opposite direction, namely clockwise). The first sensing masses 16a'-16d' are consequently aligned in respective diametric directions, which are inclined with respect to the pitch and roll axes, about which the pitch angular velocity $\vec{\Omega}_x$ and the roll angular velocity $\vec{\Omega}_y$ are applied, and moreover inclined with respect to the sides of the die 2 (and to the horizontal axes x, y).

In addition, the first sensing masses 16a', 16b' of the first pair are symmetrical to corresponding sensing masses 16d',

16c' of the second pair, with respect to the axis of symmetry of the die pads 2d (coinciding with the second horizontal axis y).

The second sensing masses 25a', 25b' are arranged in the available space left free by the first sensing masses 16a'-16d', and are, for example, aligned along the second horizontal axis y (as illustrated in FIG. 4). It may thus be noted that the arrangement of the first and second sensing masses in FIG. 4 derives, as compared to the arrangement of the same masses of FIG. 1, from a counterclockwise rotation through the angle of inclination α about the center O.

The present applicant has found that the aforesaid arrangement of the first and second sensing masses 16a'-16d', 25a', and 25b' makes it possible to achieve a series of advantages, amongst which a simplified connection of the corresponding first and second sensing electrodes 22, 23 towards the die pads 2d.

In particular, a first processing channel in the electronic read interface and corresponding electrical connections to the connection pads 2d are associated to the first pair of first sensing masses 16a', 16b', whilst associated to the second pair of first sensing masses 16c', 16d' are, in the same electronic read interface, a second and distinct processing channel, and corresponding electrical connections to the respective connection pads 2d.

The present applicant has found that in the arrangement of a known type shown in FIG. 1, the position of the first sensing masses 16a-16d with respect to the connection pads 2d of the die 2 shows a marked lack of uniformity (as do the corresponding electrical connections to the same connection pads 2d). In fact, the two pairs of first sensing masses 16a-16d are mutually positioned in an asymmetrical way with respect to the axis of symmetry of the connection pads 2d, thus calling for a different design of the electrical connections for the two processing channels. Consequently, the reading performance referred to the two axes of detection (of pitch and roll) may be different, and possibly must be compensated for by the electronic read interface (which is consequently more complex).

Instead, the arrangement described in FIG. 4 for the first sensing masses 16a'-16d' with respect to the connection pads 2d makes it possible to obtain a substantial symmetry of the electrical connections to the connection pads 2d for the two processing channels (the two pairs of first sensing masses are in fact set in an altogether symmetrical way with respect to the axis of symmetry of the connection pads 2d). The symmetry of the electrical connections enables considerable advantages to be obtained in terms of uniformity in the electrical characteristics (for example, in terms of active and parasitic capacitances, or leakage currents) and robustness to the spread of the parameters resulting from the manufacturing process.

Advantageously, the arrangement described enables an increase of the symmetry also of the electrical connections referred to the second sensing masses 25a', 25b', thus leading to an increase of uniformity in the electrical characteristics of the corresponding read electronics. In particular, the arrangement of the second sensing masses 25a', 25b' guarantees a substantial symmetry of the overall structure with respect to the axis of symmetry of the connection pads 2d, thus further simplifying the design of the electrical connections.

FIG. 5 shows a variant embodiment of the gyroscope 30, which differs from the one shown in FIG. 4 in so far as the second sensing masses 25a', 25b' are aligned along the first horizontal axis x, instead of along the second horizontal axis y. Also in this case, the same considerations made previously

still apply. In particular, this configuration intuitively enables a further increase in the symmetry of the detection structure with respect to the axis of symmetry of the die pads **2d**.

The present applicant has found that the aforesaid arrangement of the first and second sensing masses **16a'**-**16d'**, **25a'**, and **25b'** also optimizes exploitation of the space available in the gyroscope for detection of the angular velocity.

The area available for providing the detection structures, coinciding with the open region **2c** defined by the frame **2b** of the die **2**, in fact usually has a square shape (as is shown in FIG. 4 and in FIG. 6) or a rectangular shape. The arrangement of the first sensing masses **16a'**-**16d'** in directions inclined with respect to the sides of the frame **2b** and to the horizontal axes x, y enables increase of the dimensions and maximization of the sensitivity of the first sensing masses, exploiting for detection the areas at a greater distance from the axis of rotation of actuation.

In greater detail, and as is shown in FIG. 6, which represents in a simplified way just the area available (open region **2c**) of the gyroscope **30** and a first sensing mass (for example, the first sensing mass **16a'**), the conformation of the first sensing masses **16a'**-**16d'** can in this case be modified so as to improve exploitation of the space available in a radial direction, until the internal edges of the frame **2b** are approached. In a way not illustrated, also the conformation of the driving mass **3**, within the overall dimensions of which the sensing masses are housed, is in this case modified.

In particular, represented with a solid line is a variant embodiment of the first sensing mass **16a'**, having in this case a generally rhomboidal shape extending towards an internal edge of the frame **2b** and its center of gravity G' located at an arm $b_{C'}$ from the first elastic supporting elements **20**. In FIG. 6, illustrated with a dashed line, purely to facilitate a comparison between the different solutions, is a first sensing mass of a traditional type (for example, the first sensing mass **16b** of FIG. 1), having the shape, described previously, of a radial sector. The first sensing mass **16b** of a traditional type has its center of gravity G located at an arm b_C from the respective first elastic supporting elements **20**. Both of the first sensing masses illustrated are located at one and the same radial distance d between the respective first elastic supporting elements **20** and the center O.

This comparison highlights the fact that the arm b_C of the traditional sensing mass has a value visibly smaller than that of the arm $b_{C'}$ that can be obtained in the new configuration. In particular, the increase of the distance of the center of gravity G' of the first sensing masses **16a'**-**16d'** from the center O enables an increase in the driving velocity \vec{v}_a felt by the same first sensing masses (given the same angle of rotation of the driving mass **3**), and hence an increase in the Coriolis force $F_{C'}$, given that this force is directly proportional to the driving velocity \vec{v}_a . In addition, since the Coriolis force $F_{C'}$ is applied at a greater arm $b_{C'}$, the value of the resulting twisting moment increases.

In addition, this configuration allows to have available a greater surface for the sensing electrodes **22**, **23**. In general, it is thus clear that this configuration enables, with appropriate design choices, a considerable increase in the sensitivity of detection.

The present applicant has also found that the aforesaid arrangement of the first and second sensing masses **16a'**-**16d'**, **25a'**, and **25b'** makes it possible to obtain, using an appropriate configuration of the electronic read interface, a further increase in the sensitivity of the gyroscope **30**.

In detail, the gyroscope **30**, shown in FIGS. 4 and 5, has the peculiarity of having the axes of detection in the plane of the sensor xy (coinciding with the first and second diametric directions x_1 , x_2 of alignment of the first sensing masses **16a'**-**16d'**) inclined by the angle α with respect to the horizontal axes x and y about which the pitch angular

velocity $\vec{\Omega}_x$ and the roll angular velocity $\vec{\Omega}_y$ act.

Instead of envisaging assembly of the die **2** rotated by a corresponding angle α at the level of package or board, which would evidently make it possible to re-orient the axes of detection according to the original directions of pitch and roll (i.e., the horizontal axes x and y), a further aspect of the present disclosure envisages to suitably combine at the electronic read interface level the detection signals coming from the first sensing masses **16a'**-**16d'**. In particular, the detection signals are combined so as to re-obtain, starting from the capacitive variations associated to the displacements of the first sensing masses **16a'**-**16d'**, voltage outputs corresponding to the original pitch and roll directions (i.e., to the horizontal axes x and y).

In the case where the angular velocity to be detected about the first horizontal axis x or the second horizontal axis y, a unit value is considered for simplicity:

$$\Omega_x = 1^\circ/s; \Omega_y = 1^\circ/s$$

and each pair of first sensing masses **16a'**-**16d'** has a unit sensitivity S:

$$S_x = 1 \frac{mV}{^\circ/s}; S_y = 1 \frac{mV}{^\circ/s}$$

Intuitively, in the case of a traditional configuration (for example, of the type illustrated in FIG. 1, having first sensing masses **16a**-**16d** aligned along the horizontal axes x, y), the following voltage values would be obtained at an output from the electronic read interface:

$$V_{out,x} = 1mV; V_{out,y} = 1mV$$

where $V_{out,x}$ is the output voltage corresponding to the first pair of first sensing masses **16a**, **16b** aligned along the first horizontal axis x, and $V_{out,y}$ is the output voltage corresponding to the second pair of first sensing masses **16c**, **16d** aligned along the second horizontal axis y (in the traditional solution).

In particular, as described previously, an angular velocity (of pitch or roll) about one of the horizontal axes x, y would determine a capacitive unbalancing of a single pair of first sensing masses **16a**-**16d** (in particular the pair aligned about the same horizontal axis).

Instead, in the new configuration illustrated in FIG. 4 or in FIG. 5, an angular velocity (of pitch or roll) about one of the horizontal axes x, y determines a capacitive unbalancing of both of the pairs of first sensing masses **16a'**, **16b'** and **16c'**, **16d'**, in so far as they are sensitive to the components of the angular velocities of pitch and roll along the diametric directions x_1 and x_2 , and these components have a non-zero value for both of the pairs. Given the same geometry and distance from the center O of the first sensing masses **16a'**-**16d'**, in this case the following total output voltages for the horizontal axes x, y are obtained:

$$V_{out,x} = V_{out,x1} + V_{out,x2} = \frac{1}{\sqrt{2}}mV + \frac{1}{\sqrt{2}}mV = \sqrt{2}mV$$

$$V_{out,y} = V_{out,y1} + V_{out,y2} = \frac{1}{\sqrt{2}}mV + \frac{1}{\sqrt{2}}mV = \sqrt{2}mV$$

where $V_{out,x1}$ and $V_{out,x2}$ are the output voltages corresponding to the first pair and, respectively, to the second pair of

first sensing masses **16a'-16d'**, aligned, respectively, in the first and second diametric directions x_1 , x_2 .

Consequently, although the capacitive unbalancing of the single first sensing masses referred to a given angular velocity is smaller by a factor $1/\sqrt{2}$ with respect to the corresponding unbalancing in a traditional configuration, it is possible to sum (via a purposely configured read interface) the contributions of all four of the first sensing masses referred to the same angular velocity, and obtain a global increase in the sensitivity of the gyroscope **30** by a factor $\sqrt{2}$.

FIG. 7 illustrates an electronic device **40**, which comprises the microelectromechanical gyroscope **30** described previously. The electronic device **40** can advantageously be used in a plurality of electronic systems, for example, in inertial navigation systems, in automotive systems, or in systems of a portable type, such as, for example: a PDA (Personal Digital Assistant); a portable computer; a cell phone; a digital audio player; a photographic camera or a camcorder; or further systems capable of processing, storing, transmitting, and receiving signals and information.

The electronic device **40** further comprises: a driving circuit **41**, operatively coupled to the driving assembly **4** for imparting the rotary driving movement to the driving mass **3**, and supplying biasing signals to the microelectromechanical structures; a read circuit **42**, operatively coupled to the sensing electrodes **22**, **23** of the first and second sensing masses, for detecting the amount of displacement of the same sensing masses and hence determining the angular velocities acting on the structure; and an electronic control unit **44**, for example, of a microprocessor type, connected to the read circuit **42**, and designed to supervise the general operation of the electronic device **40**, for example, on the basis of the angular velocities detected and determined. In particular, the read circuit **42** includes the aforesaid electronic read interface, designed to appropriately combine the output signals corresponding to the individual first sensing masses, in order to increase the sensitivity of detection, as described previously.

The advantages of the microelectromechanical gyroscope provided according to the present disclosure are clear from the foregoing description.

In any case, it is once again emphasized that the configuration of the sensing masses makes it possible to optimize exploitation of the area available for detection, increase the sensitivity of the sensor, and improve uniformity of the electrical characteristics and the robustness of the system to disturbance. More in general, this configuration allows improving the characteristics and the electrical performance of the microelectromechanical gyroscope.

Finally, it is clear that modifications and variations can be made to what has been described and illustrated herein, without thereby departing from the scope of the present disclosure.

In particular, it is evident that the new configuration of the first sensing masses can advantageously be provided for a gyroscope that is only biaxial, i.e., not sensitive to yaw angular velocity (and hence without the second sensing masses **25a'**, **25b'**).

For specific design requirements, the value of the angle α may differ from the value described, and be, for example, comprised between 40° and 50° . The angles of inclination of the two pairs of first sensing masses **16a'-16d'** with respect to the first horizontal axis x may also not be the same, the two pairs of first sensing masses having in any case opposite inclination with respect to the first horizontal axis x , but in this case no longer be symmetrical with respect to the second

horizontal axis y . In addition, the two diametric directions x_1 and x_2 may not be orthogonal to one another.

In addition, the die pads **2d** can extend in a different direction, for example, along the second horizontal axis y .

In a per-se known manner, the displacement of the sensing masses can be determined with a technique different from the capacitive one, for example, by detection of a magnetic force.

In addition, the twisting moment for causing oscillation of the driving mass with rotary movement can be generated in a different way, for example, by means of parallel-plate electrodes, or else by magnetic actuation.

More in general, it is evident that the configuration of some structural elements of the gyroscope may be different. For example, the driving mass **3** may have a shape different from the circular one, such as a generally closed polygonal shape, as likewise the shape of the frame **2b** of the die **2** can be different. Alternatively, it is possible to envisage a different arrangement of the first elastic anchorage elements of the driving mass **3** (which must be in any case able to perform decoupling of the driving mass from the motion of detection), or of the second elastic supporting elements **28** (which must be in any case such as to enable the radial movement of the sensing masses of the second type). In addition, a different configuration of the sensing electrodes associated to the sensing masses of the first and second types can be envisaged.

The various embodiments described above can be combined to provide further embodiments. All of the U.S. patents, U.S. patent application publications, U.S. patent applications, foreign patents, foreign patent applications and non-patent publications referred to in this specification and/or listed in the Application Data Sheet are incorporated herein by reference, in their entirety. Aspects of the embodiments can be modified, if necessary to employ concepts of the various patents, applications and publications to provide yet further embodiments.

These and other changes can be made to the embodiments in light of the above-detailed description. In general, in the following claims, the terms used should not be construed to limit the claims to the specific embodiments disclosed in the specification and the claims, but should be construed to include all possible embodiments along with the full scope of equivalents to which such claims are entitled. Accordingly, the claims are not limited by the disclosure.

The invention claimed is:

1. A device, comprising:

a substrate;

a rectangular frame formed on the substrate, a first side of the frame extending along a first axis and a second side of the frame extending along a second axis that is orthogonal to the first axis;

a driving assembly elastically coupled to the substrate and positioned within the frame, at least a portion of the driving assembly being configured to move in a plane;

a first pair of sensing masses coupled to the driving assembly and positioned within the frame, the first pair of sensing masses aligned with each other along a third axis, the third axis being transverse to the first axis, the first pair of sensing masses being configured to move out of the plane to generate a first signal indicative of rotation about the first axis and rotation about the second axis;

a second pair of sensing masses coupled to the driving assembly, the second pair of sensing masses aligned with each other along a fourth axis, and the fourth axis being orthogonal to the third axis, the second pair of

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- sensing masses being configured to move out of the plane to generate a second signal indicative of rotation about the first axis and rotation about the second axis; and
- a read circuit coupled to the first pair of sensing masses and the second pair of sensing masses, the read circuit configured to detect rotation about the first axis based on the first and second signals from the first pair of sensing masses and the second pair of sensing masses, respectively.
2. The device of claim 1 wherein the first pair of sensing masses and the second pair of sensing masses have a non-rectangular shape.
3. The device of claim 2 wherein each sensing mass of the first pair of sensing masses and the second pair of sensing masses includes an outermost point formed from an intersection of a first side and a second side, the first side being substantially parallel to the first axis and the second side being substantially parallel to the second axis.
4. The device of claim 1 wherein the rectangular frame has a height from the substrate to a top surface of the rectangular frame and the first pair of sensing masses are suspended above the substrate by a distance, the height being greater than the distance.
5. The device of claim 2, further comprising a central anchor, each sensing mass of the first pair and the second pair of sensing masses including a plurality of outer edges, a smallest one of the outer edges being closer to the central anchor than the other outer edges.
6. The device of claim 2 wherein each sensing mass includes at least five outer edges.
7. A device, comprising:
- a substrate having a surface that includes a first axis and a second axis perpendicular to the first axis;
 - a central anchor, the first axis and the second axis cross each other at the central anchor;
 - a plurality of driving electrodes on the substrate;
 - a first pair of sensing masses positioned on opposite sides of the central anchor, the first pair of sensing masses being aligned with each other along a third axis that is shifted approximately 45 degrees from the first axis;
 - a second pair of sensing masses positioned on opposite sides of the central anchor, the second pair of sensing masses aligned with each other along a fourth axis that is shifted approximately 45 degrees from the first axis; and
 - a read circuit coupled to the first and second pair of sensing masses, the read circuit configured to detect rotation about the first axis from signals from both the first and second pair of sensing masses and to detection rotation about the second axis from signals from both the first and second pair of sensing masses.
8. The device of claim 7 wherein the plurality of driving electrodes are positioned around the central anchor.
9. The device of claim 7 wherein each sensing mass of the first pair and the second pair have a non-rectangular shape.
10. The device of claim 9 wherein each sensing mass includes an outermost point spaced furthest from the central anchor that is formed by an intersection of two edges.
11. The device of claim 10, further comprising a rectangular frame including a first side that extends along the first axis and a second side that extends along the second axis.
12. The device of claim 11 wherein a first one of the two edges of each sensing mass is substantially parallel to the first axis and a second one of the two edges is substantially parallel to the second axis.

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13. A device, comprising:
- a rectangular frame, the frame having a first side that extends substantially parallel to a first axis and a second side that extends substantially parallel to a second axis, the second axis being transverse to the first axis;
 - a central anchorage, the first axis crosses the second axis at the central anchorage;
 - a first pair of suspended sensing electrodes within the frame, the first pair of sensing electrodes being aligned with each other along a third axis that is at a non-zero angle of inclination with respect to the first and the second axis;
 - a second pair of suspended sensing electrodes within the frame, the second pair of sensing electrodes being aligned with each other along a fourth axis that is at a non-zero angle of inclination with respect to the first and the second axis; and
 - a read circuit configured to detect rotation about the first axis in response to signals from both the first pair of sensing electrodes and the second pair of sensing electrodes.
14. The device of claim 13 wherein the non-zero angle of inclination of the third axis is approximately 45 degrees.
15. The device of claim 14 wherein the non-zero angle of inclination of the fourth axis is approximately 45 degrees.
16. The device of claim 13 wherein each suspended sensing electrode of the first and second pair has a non-rectangular shape.
17. The device of claim 16 wherein each suspended sensing electrode of the first and second pair includes an outermost point that is farther from the central anchorage than any other part of the suspended sensing electrode.
18. The device of claim 13 wherein each suspended sensing electrode of each of the first and second pair includes a first non-rectangular portion and a second non-rectangular portion, the first non-rectangular portion being between the second non-rectangular portion and the central anchorage.
19. The device of claim 18 wherein the second non-rectangular portion has a larger area than the first non-rectangular portion.
20. A device, comprising:
- a rectangular frame, the frame having a first side that extends substantially parallel to a first axis and a second side that extends substantially parallel to a second axis, the second axis being transverse to the first axis;
 - a first pair of suspended sensing electrodes within the frame, the first pair of sensing electrodes being aligned with each other along a third axis that is at a non-zero angle of inclination with respect to the first and the second axis, the first pair of sensing electrodes configured to generate a first signal indicative of rotation about the first axis and the second axis;
 - a second pair of suspended sensing electrodes within the frame, the second pair of sensing electrodes being aligned with each other along a fourth axis that is at a non-zero angle of inclination with respect to the first and the second axis, the second pair of sensing electrodes configured to generate a second signal indicative of rotation about the first axis and the second axis; and
 - a plurality of contact pads aligned along the first side of the frame along the first axis, each of the first and second pairs of sensing electrodes being coupled to the plurality of contact pads.
21. The device of claim 20, further comprising a read circuit configured to detect rotation about the first axis in

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response to the first signal and the second signal from the first pair of sensing electrodes and the second pair of sensing electrodes.

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